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14. ABSTRACT
In the last decade, synthetic jets have emerged as one of the leading active flow control technologies for aerodynamic flows. Synthetic jets have high appeal because they are zero-net-mass-flux flows that achieve significant control authority by coupling to the unsteady dynamics of the flow-field. While applications of synthetic jets abound, only a very limited description of the synthetic jet control effect exists. Such a limited description significantly constrains our current ability to optimize the use of these flows in complex flow configurations, and impairs the development of advanced numerical simulations that can accurately predict these flows. The current work intended to address the deficiencies in our ability to describe and understand synthetic jet control of a boundary layer flow, and to provide a description of the flow-field that improved numerical simulations of synthetic flow control. The approach in this study was experimental and involved obtaining highly-resolved velocity field measurements for a synthetic jet interacting with a cross-flow boundary layer. These measurements were to be obtained by examining the synthetic jet cross-flow interaction in a novel matched-index-of-refraction (MIR) flow facility.

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SYNTHETIC JET FLOW CONTROL IN A
MATCHED-INDEX-OF-REFRACTION FLOW FACILITY

FA9550-07-1-0387

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Abstract

In the last decade, synthetic jets have emerged as one of the leading active flow control technologies for aerodynamic flows. Synthetic jets have high appeal because they are zero-net-mass-flux flows that achieve significant control authority by coupling to the unsteady dynamics of the flow-field. While applications of synthetic jets abound, only a very limited description of the synthetic jet control effect exists. Such a limited description significantly constrains our current ability to optimize the use of these flows in complex flow configurations, and impairs the development of advanced numerical simulations that can accurately predict these flows. The current work intended to address the deficiencies in our ability to describe and understand synthetic jet control of a boundary layer flow, and to provide a description of the flow-field that improved numerical simulations of synthetic flow control. The approach in this study was experimental and involved obtaining highly-resolved velocity field measurements for a synthetic jet interacting with a cross-flow boundary layer under conditions representative of flow control applications. These measurements were to be obtained by examining the synthetic jet cross-flow interaction in a novel matched-index-of-refraction (MIR) flow facility. The measurements were then to be used to develop physical models of the flow-field interaction in the near- and far-field of the interaction.

1 Objectives

A review of synthetic jet flow control research reveals that the primary deficiency in our current understanding lies with the interaction of a synthetic jet with a simple cross-flow. For example, the changes in the interaction, as the formation conditions of the synthetic jet change, are not well understood. A good physical description of the flow-field is not available, and as a consequence, we lack even a rudimentary description of how the interaction forms and evolves with time. Moreover, the important changes that occur in the cross-flow farther downstream, the changes that ultimately enforce the control effect from the synthetic jet, have never been examined in detail. In addition, as we lack a good physical description of the synthetic jet when it interacts with a cross-flow, the state-of-the-art in numerical simulations of synthetic jet flows is lagging behind the current need. The best quantitative agreement between simulations and experiments requires an LES approach (Rumsey et al. 2006) which is still far from affordable for aerodynamic flow control applications. A robust computational approach to synthetic jet flows is very much demanded if synthetic jets are to be integrated quickly and efficiently into existing and future aircraft platforms where the true potential of these devices can be realized.

The motivation for this work was to directly address the current deficiencies in our ability to describe and our understanding of the interaction of a synthetic jet with a cross-flow boundary layer. This understanding was to be obtained by examining the synthetic jet cross-flow interaction in a novel matched-index-of-refraction (MIR) flow facility. With this facility in place, it would have been possible to examine in detail the near- and far-fields of the synthetic jet-cross flow interaction, to propose flow scaling arguments for the interaction, and to understand how synthetic jets effect control in large aerodynamic flows. To this end, the specific objectives of the research program were

1. to acquire the MIR flow facility, and to design and manufacture the transparent models for the experimental testing

2. to obtain time-resolved, three-dimensional measurements of the synthetic jet-cross flow interaction in the near- and far-fields of the synthetic jet actuator orifice

3. to examine how the near-field flow scales with the dimensionless groups, $\mathrm{L}_\circ/\mathrm{D}_\circ$, $\mathrm{L}_\circ/\delta$, $\mathrm{Re}_{\mathrm{U}_\circ}$, $(\mathrm{U}_\circ/\mathrm{U}_\infty)^2$

4. to examine the near-field interaction dynamics of the synthetic jet vortex rings and the vorticity in the incoming boundary layer

5. to describe the near-field flow topology using critical point methods (Perry and Chong 1987), and from the flow topology propose a vortex model of the interaction (Perry and Hornung 1984)

6. to examine the changes in the far-field mean flow and turbulence, and to propose scaling relationships based on the dimensionless groups, $\mathrm{L}_\circ/\delta$, $\mathrm{Re}_{\mathrm{U}_\circ}$, $(\mathrm{U}_\circ/\mathrm{U}_\infty)^2$

7. to work with the CFD community in revising boundary layer turbulence models for flows with synthetic jet flow control

8. to encourage new, hybrid approaches, such as Detached Eddy Simulations (DES), towards computing these flows by providing a benchmark database for validating and verifying numerical solutions of synthetic jet flows

2 Approach

The research to be undertaken in this project was to have provided a set of unique spatial and temporal measurements of the synthetic jet-cross flow interaction. The approach would use a matched-index-of-refraction (MIR), water-based, recirculating flow facility to gain undistorted optical access to the synthetic jet flow field. In this facility, the synthetic jet generator would be fabricated from optically-transparent acrylic, and the working fluid would be an aqueous solution of sodium iodide with a solution concentration that gives an index of refraction identical to the index of refraction of the acrylic. The facility design is based on the same principles used to design the matched-index-of-refraction flow facility at The Johns Hopkins University (Uzol et al. 2002).

The success of this project depended critically on obtaining highly-resolved measurements of the synthetic jet cross-flow interaction. Well-resolved measurements are, in turn, intimately tied to the scale of the facility. The size of the proposed facility was estimated by balancing the facility construction and operating costs against the competing priority of well-resolved, flow-field measurements that are uncontaminated by the finite size of the flow facility. This estimate required a facility with a cross-section that is, approximately, 0.5 m on a side, and a combined test section length of approximately 2 m. Two manufacturers (Engineering Laboratory Design and Rolling Hills Research Corp.) had products that met those requirements with only minor modifications.

The above-described flow facility would have permitted an unprecedented view of the synthetic jet-cross flow interaction, and to exploit this advantage, an experimental program was to have been undertaken to examine, independently and in great detail, the near- and far-field regions of the interaction. Stereoscopic particle image velocimetry (PIV) was to be used to measure the three components of velocity within the synthetic jet flow. The measurements would have been synchronized to the unsteadiness in the synthetic jet, permitting the accumulation of time accurate snapshots of the flow field. In the near-field, these measurements would have been used to examine the interaction of the coherent vorticity from the synthetic jet with the vorticity in the upstream boundary layer to reveal how the incoming boundary layer is changed downstream. In the far-field, where the description of the flow is statistical in nature, ensemble-averaged velocity measurements would have been obtained for statistical analysis and evaluation. The far-field measurements would then be used to examine the changes in the turbulence statistics to provide insight into how current turbulence models must be modified to account for the upstream interaction between the boundary layer and the synthetic jet.

3 Accomplishments

3.1 Quiescent Environment Matched-Index-of-Refraction Facility and Results

In the first year of the project, a matched-index-of-refraction (MIR) quiescent fluid facility was built. This facility used a plunger-driven synthetic jet actuator to examine the flow in the orifice of a model synthetic jet actuator in a quiescent ambient environment. The actuator was located at one end of a rectangular tank and was designed to permit testing of synthetic jet actuators with different orifice geometries. The facility was also used to gain experience with the process of using sodium iodide solution as a working fluid. A particular challenge in using a concentrated solution of aqueous sodium iodide as the working fluid is that the solution must be excluded from visible light and oxygen to prevent the formation of I_3^- ions. These ions absorb light in the visible portion of the spectrum and degrade the light signal in PIV measurements. To some extent the formation of these ions cannot be avoided during the mixing of the sodium iodide salt with the water. The resulting solution has a yellowish tinge to it, and PIV measurements with this solution were not satisfactory. The ion formation process is reversible with the addition of sodium borate 10-hydrate ($Na_2B_4O_7.10H_2O$). The solution is then kept under a blanket of pure nitrogen.

Once a technique for obtaining and maintaining a clear solution was established, the solution concentration in the facility was adjusted to match the index-of-refraction between the fluid and clear acrylic for the green light used in the PIV measurements. Velocity field measurements were then obtained in the facility for a synthetic jet created at a circular orifice; the measurements include detailed time-resolved velocity fields of the flow in the actuator orifice and two orifice diameters downstream of the orifice.

Sample measurements for the formation of a synthetic jet at a circular orifice for one non-dimensional stroke and Reynolds number are shown in Fig. 1. These figures show the velocity vector field and contours of the horizontal velocity component at six phases during the actuator cycle. These data fields were obtained by phase-averaging over 64 individual realizations. These figures illustrate well the advantage of a solid-fluid index matching. The velocity information in the orifice at $-0.5 \leq x_c/D \leq 0.0$ was obtained by viewing the fluid motion through 100 cm of polished acrylic. In these six figures, the first four show portions of the expulsion phase of the actuator cycle. Of particular note is the higher velocity fluid around the interior perimeter of the orifice. This fluid, with lower initial velocity due viscous effects and separation during the ingestion stroke, responds more rapidly to the changing pressure gradient across the orifice as the actuator stroke changes from ingestion to expulsion. A rounded interior edge to the orifice minimizes flow separation, and by Phase 8, the velocity appears mostly uniform across the interior of the orifice. The formation of the vortex ring is well-resolved. The last two sub-figures show the ingestion stroke near its beginning and end. Clearly, the presence of the newly-formed vortex ring at the orifice exit inhibits the ingestion of fluid near the center of the orifice, and the initial acceleration of the fluid occurs around the orifice perimeter with some separation due to the sharp edge of the orifice exit. A stagnation point near the orifice exit plane is clearly evident, and this point appears to move away from the orifice as the ingestion stroke continues. By Phase 15, there is a mostly uniform velocity field in the orifice.

To gain a sense for the spatial and temporal variations of the velocity field in the orifice, profiles of the horizontal velocity component were extracted the velocity field data. Figure 2 shows two sets of velocity profiles, one set at the orifice entrance ($x_c/D = -0.5$, left column) and one set at the orifice exit ($x_c/D = 0.0$, right column). All eighteen phases of the actuator cycle are shown, but for clarity only six phases are shown in any given plot. An arrow in the figure indicates the evolution of the profiles with increasing time. Looking across the rows shows the difference in the velocity profile at the entrance and exit to the orifice for the same times. After some careful inspection, it becomes apparent that the 'ingesting' side of the orifice tends to lag behind the 'expelling' side of the orifice: compare sub-figures (a) and (b) or sub-figures (e) and (f). When fluid is expelled from the orifice (during either half-stroke), the profiles exhibit common features with local peaks around the orifice perimeter and uniform regions closer to the orifice axis. Of particular note is the reverse flow around the perimeter of the orifice entrance in sub-figure (e). This reverse flow is due to flow separation at the sharp edge of the orifice exit and contributes to the rapid acceleration of the flow at the orifice exit once the expulsion stroke begins.

3.2 Missed Accomplishments

The initial studies highlighted above were undertaken at the beginning of the grant as a DURIP proposal was being developed and submitted. This proposal effort was undertaken to obtain funding to acquire, adapt, and operate a recirculating matched-index-of-refraction facility using aqueous sodium iodide as the working fluid. The proposal was ultimately successful, but the funding was delayed by six months. Once the funding was in place, an Request for Proposals was issued by the University and a down-select process was undertaken resulting in an award to Engineering Laboratory Design (ELD) in February of 2009. An artist's sketch of the anticipated facility is shown in Fig. 3. An original delivery date of August 2009 was not met by the vendor, and the PI is still awaiting delivery of the facility. Under normal circumstances, the PI would have requested a No-Cost Extension for the project, but the PI has since taken a detail assignment at AFOSR to manage the research portfolio out of which this project was managed. To prevent a perceived conflict of interest, the grant has been allowed to expire, and the final year of funding, in addition to a portion of the DURIP funding, has been returned to AFOSR.

3.3 Recommended Future Work

Despite the lapses in the current grant, the PI still believes in the value of the proposed work and strongly endorses continuing work in this area in the future. A two year research program based on the original proposal is outlined below, and if undertaken at some point, it will directly address the current deficiencies in our ability to describe and our understanding of the interaction of a synthetic jet with a cross-flow boundary layer.

In the first year, experimental measurements for a round synthetic jet in a cross-flow should be undertaken. In these tests, a laminar boundary layer should initially be maintained on the plate. Near-field measurements can examine the flow in the immediate vicinity of the orifice and should focus on a field-of-view approximately $2D_\circ$ on a side. The interaction should also be examined with a field of view extending from $2D_\circ$ upstream of the orifice to approximately $5D_\circ$ downstream of the orifice. These measurements should be obtained in streamwise-oriented planes beginning on the centerline of the interaction and progressing across the span of the interaction at intervals of one-tenth of the orifice diameter. The test conditions should also include a range of synthetic jet formation parameters ($L_\circ/D_\circ$, $Re_{U_\circ}$) at different values of $(U_\circ/U_\infty)^2$. As the measurements become available, an analysis of the flow topology for the near-field can begin along with the development of a vortex-based model for the unsteady near-field interaction.

Once the near-field measurements are completed, the far-field of the interaction should be examined. In the far-field, ensemble-averaged measurements beginning at $5D_\circ$ downstream of the orifice and extending downstream to 20-50$D_\circ$ can be made. The measurements should be obtained in streamwise-aligned planes beginning on the centerline of the interaction and extending across the span of the flow to the edge of the interaction, a distance which will depend on the streamwise position of the measurement.

In the second year of the project, the analysis of the round synthetic jet near-field interaction should be completed with the development of a vortex-based model of the unsteady interaction at the orifice. A statistical analysis of the far-field boundary layer data should also be undertaken in Year Two. This effort should begin by comparing the boundary layer turbulence structure downstream of the interaction to benchmark turbulent boundary layer data at similar Reynolds numbers. The scaling of the far-field flow on the synthetic jet formation parameters can also be examined.

An experimental effort in Year Two of the project should focus on experimental measurements for the rectangular synthetic jet in a cross-flow. For this flow, the characteristic actuator dimension in the streamwise direction is the rectangular slot height, h. Near-field measurements should be obtained in the immediate vicinity of the synthetic jet slot, and in a region extending 2h upstream of the slot and 5h downstream of the slot. These measurements should be obtained in streamwise-oriented planes beginning on the centerline of the slot and extending in the spanwise direction at intervals of one-tenth of the slot width, w.

The experimental component of the project can then conclude with measurements for the rectangular synthetic jet interaction in the far-field extending from 5h downstream of the slot to 20-50h downstream. With the measurements for the round and rectangular synthetic jet interactions complete, the effort can then make detailed comparisons between these two interactions, and should work with the computational community to develop improved simulations of synthetic jet flows.

Acknowledgment/Disclaimer

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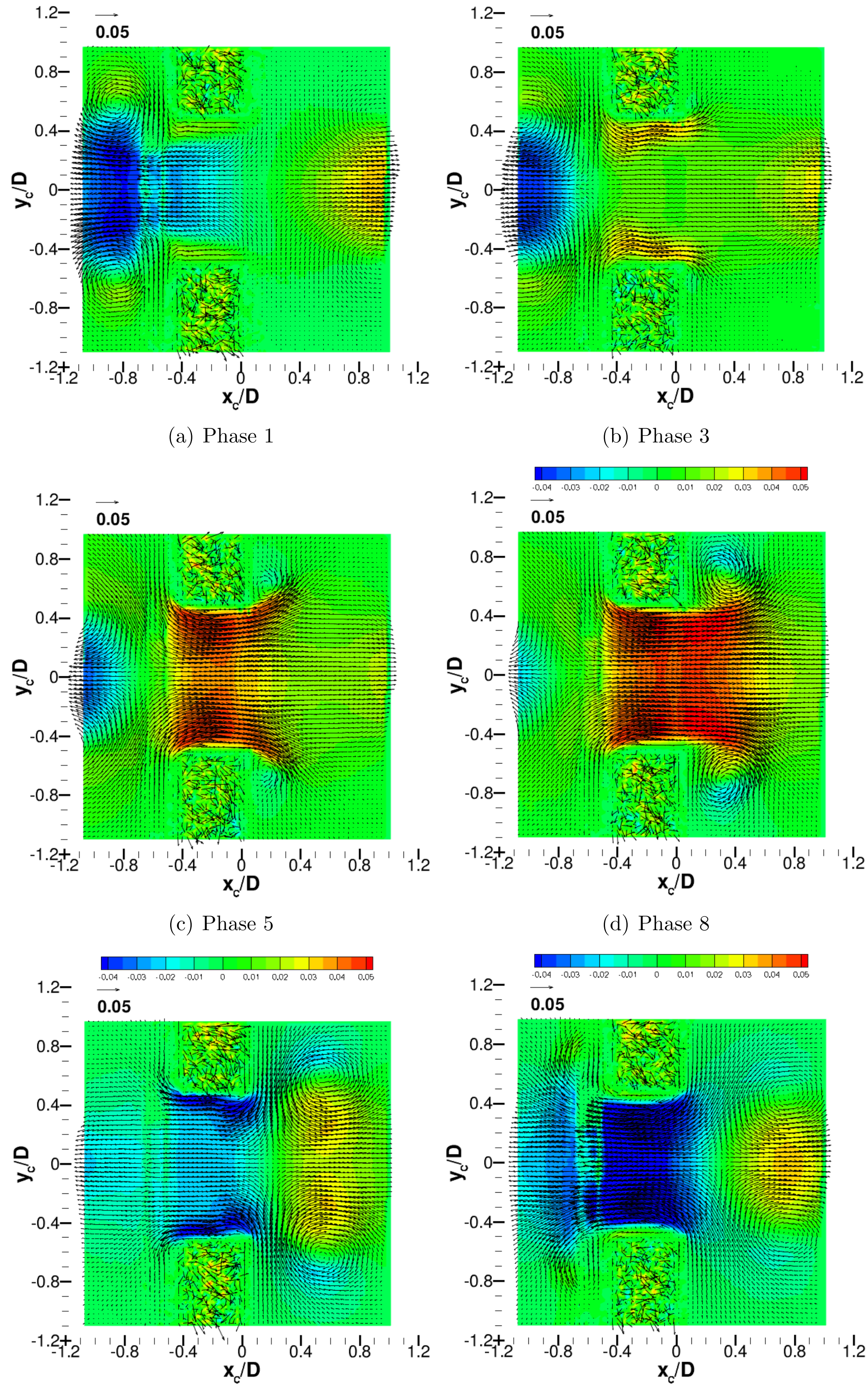
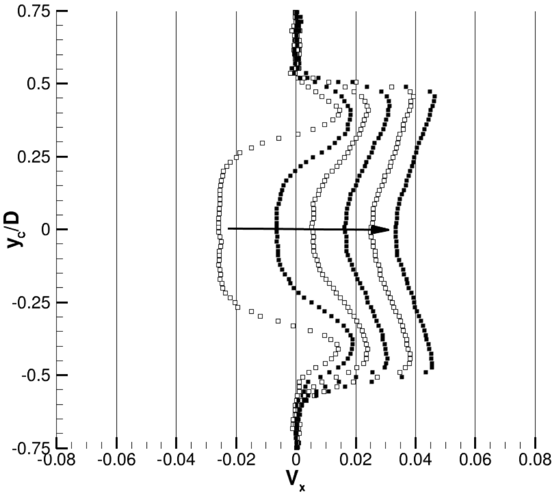


(a) Phase 1 (b) Phase 3

(c) Phase 5 (d) Phase 8

(e) Phase 11 (f) Phase 15

Figure 1: Velocity vector fields and contours of the horizontal component of velocity at six phases during the actuator cycle.



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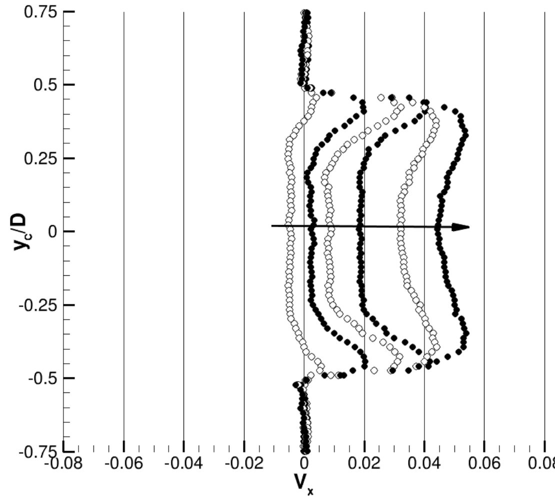

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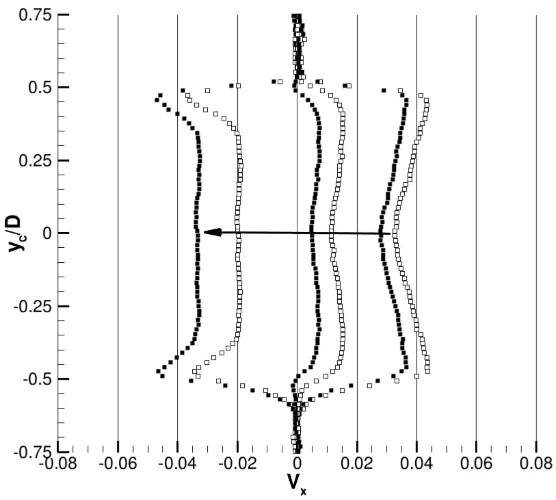

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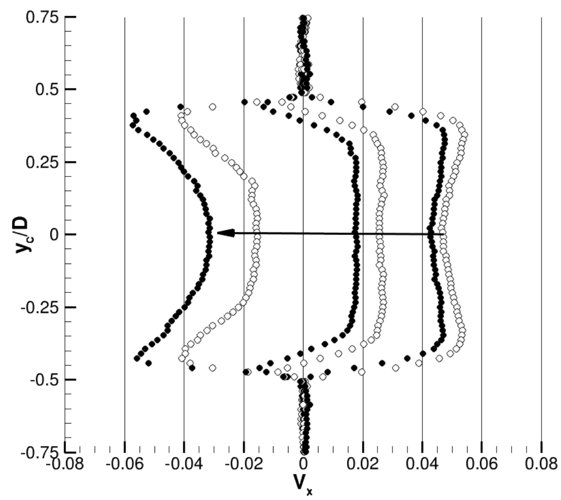
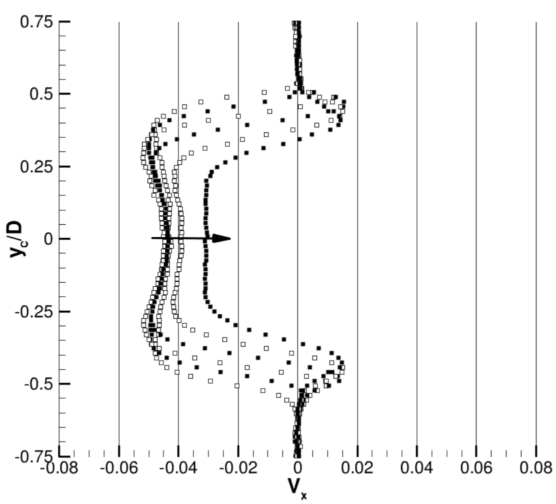
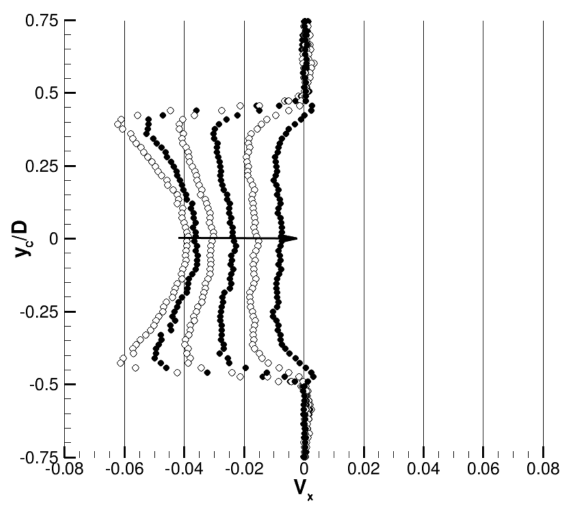


(d) Phases 7–12



(e) Phases 13–18



(f) Phases 13–18

Figure 2: Velocity profiles at the entrance (left column, (a,c,e)) and exit (right column, (b,d,f)) to the orifice.

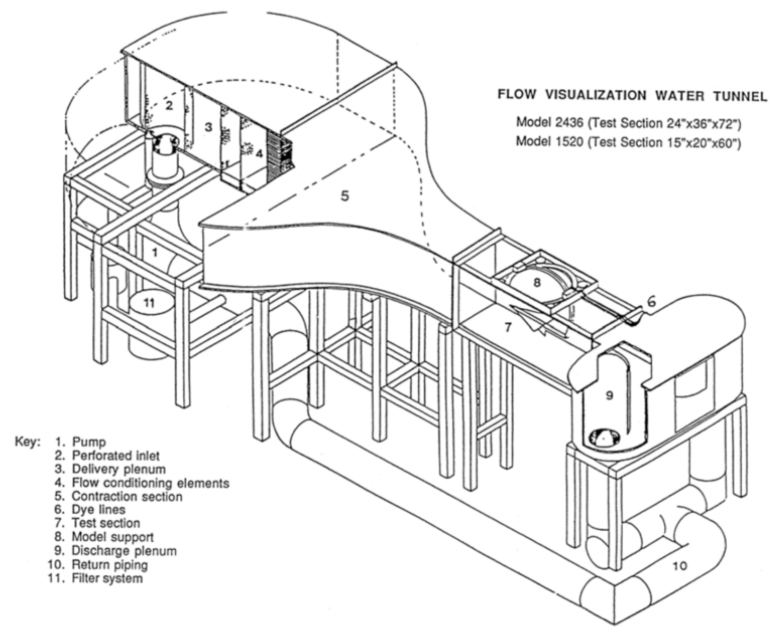


Figure 3: Drawing of the matched-index-of-refraction flow facility for studying the interaction of a synthetic jet with a cross-flow.